

## Article

# A Study on the Properties of Geopolymer Concrete Modified with Nano Graphene Oxide

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**Abstract:** This paper reports the results of a study conducted to examine the impacts of adding graphene oxide (GO) to GBFS-fly ash-based geopolymer concrete. The geopolymer concrete's compressive strength, thermal conductivity, and modulus of elasticity were assessed. X-ray diffraction (XRD) analysis was conducted to understand the differences in mineralogical composition and a rapid chloride penetration test (RCPT) to investigate the changes in the permeability of chloride ions imposed by GO addition. The results showed that adding 0.25 wt.% GO increases the modulus of elasticity and compressive strength of GBFS-FA concrete by 30.5% and 37.5%, respectively. In contrast, permeability to chloride ions was reduced by 35.3% relative to the GO-free counterparts. Thermal conductivity was decreased as GO dosage increased, with a maximum reduction of 33% being observed in FA65-G35 wt.% samples. Additionally, XRD showed the suitability of graphene oxide in geopolymer concrete. The present research demonstrates very promising features of GO-modified concrete that exhibit improved strength development and durability compared to traditional concrete, thus further advocating for the wider utilization of geopolymer concrete manufactured from industrial byproducts.

**Keywords:** graphene oxide; geopolymer concrete; alkali-activated materials; nanomaterials

## 1. Introduction

Approximately 8% of the world's carbon dioxide (CO<sub>2</sub>) emissions can be related to clinker manufacturing [1], and the global cement production has been growing 10–12% per year over the last decade [2,3]. In order to reduce the outflow of CO<sub>2</sub> emissions, it is vital to restrict clinker manufacturing [4,5] and partially replace it with supplementary cementitious materials (SCM) [6,7]. Granulated blast furnace slag (GBFS) [8] and fly ash (FA) are both industrial by-products [8–10] that have been extensively utilized as SCMs to diminish the clinker factor in cement formulae [11]. However, SCMs have a limited ability to substitute clinker with a current threshold limit at approximately 25–35% of cement weight due to the significant decrease in concrete strength at an early age. Recently, clinker-free binders are attracting increasing attention [4], with several studies been conducted on alkali-activated materials (AAMs) and geopolymers. Geopolymer binders might be an

eco-friendly substitute for ordinary Portland cement in various building materials, such as unreinforced and reinforced concrete composites, thermal and acoustic insulation, and fire protection coatings [12–14]. Coal fly ash is an industrial by-product of coal power plants, and every year, 70–80% of the world's ash has this origin [15,16]. Fly ash-based geopolymer concrete has been reported with engineering characteristics comparable to OPC concrete made with cement of a strength of a similar grade and increased durability [17–23]. GBFS is a by-product from iron manufacturing in blast furnace plants and can be utilized as precursor in geopolymer concrete (GPC) [24,25]. The higher strengths of GBFS and FA geopolymer concrete are mainly ascribed to the nature of the gel formed, a three-dimensional polymer-like chain structure [26].

However, when the precursors are not reactive enough, temperature curing is essential to quicken the polymerization reaction and enhance the strength of GBFS-fly ash-based GPC composites [27]. At ambient curing, the strength developed can be dilatory because of the slow process of geopolymerization. However, the high calcium content of GBFS may be used to counteract low-early age strength development and produce GPC with suitable properties for engineering purposes [28–31]. Past studies have suggested that when GBFS is introduced in fly ash-based GPCs, it improves geopolymer concrete's microstructure and mechanical properties [25,32,33]. However, there have been limited studies on geopolymer concretes with the addition of nanomaterials [34–39], and very few studies are available on the microstructure analysis and material behavior of GBFS fly ash-based GPC incorporating nanomaterial [40–42]. Relevant research gaps include the description of stress-strain relationships, permeability, and mechanisms of corrosion.

Exploratory research has been performed to describe the mechanism of corrosion of silica fume, slag, and fly ash-based GPC with high-to-low acid concentrations, and the results suggest that the geopolymer can exhibit a higher strength and enhanced durability compared to metakaolin-based geopolymers [43–45]. The lack of internationally recognized procedures to assess the performance of GPC in various environments has paved the way to the adoption different testing methods and protocols, thus resulting in inconsistent outcomes and actions to improve GPC performance. Yet, the few research studies have available seem to argue in favor of the improvement of geopolymer concrete characteristics using graphene oxide. Graphene oxide is recognized as an innovative competent material that has become a prevalent worldwide due to its relatively low cost when compared to carbon nanotubes (single- and double-walled) and carbon nanofibers [46,47]. Oxygenated sheets of GO are more amicable to binders [48], which allows them to behave as nuclei and enhance hydration and polymerization reaction, yielding further binder formation [49]. Novoselov et al. [50] utilized graphite to attain GO by adopting a micromechanical process. Because of the carbon atoms that are in the shape of hybridization, graphene is known as the material with a structure in the form of a honeycomb. The modified Hummer technique could be utilized to oxidize graphite and develop GO with more than 30.0% oxygen in its structure, which can be then included in cement-like products [51]. Preliminary laboratory results suggest that 0.04 wt.% of graphene oxide can considerably enhance the mechanical characteristics of Portland cement with increases in strength surpassing 77.0%. Microstructural analysis has shown the regulating effects of GO in the Portland cement hydration process and downstream improvement of strength. Similarly, the uniform distribution of GO has been reported in the geopolymer matrix [52], with GO particles experiencing restructuration, however. Still, scanning electron microscopy (SEM) images showed that graphene oxide-based geopolymer concrete results in a packed structure [53]. Therefore, graphene oxide can be potentially used to improve the characteristics of GBFS-FA geopolymer concrete [54–57], and this hypothesis is further investigated in the work.

### Research Significance

The current study focuses on the effects of graphene oxide addition on granulated blast furnace slag and fly ash-based geopolymer composite concrete. First, a detailed characterization analysis was performed on graphene oxide comprising EDX and XRD. GBFS-FA geopolymer samples have been produced with different GO dosages and their properties examined over time. The list of properties investigated included compressive strength (7, 28, 56, and 90 days), modulus of elasticity, thermal conductivity, and chloride penetration. According to the author's best information, no study is present on evaluating such properties in GO-modified geopolymer concrete, which marks the novelty of the present study. In addition, an equation was developed to evaluate the modulus of elasticity of geopolymer concrete using different construction codes, past studies, and results of the current study, which has not been performed previously. The comparison was performed with the results of this study with past data and observing whether the present study's equation for modulus of elasticity lies within the range of previous data. Finally, XRD analysis was conducted to examine the phase formed in GO in geopolymer concrete-blends and correlate such mineralogy structures with observed physical properties.

## 2. Experimental Plan

### 2.1. Materials

The materials used in the current research were granulated blast furnace slag, class F fly ash, graphene oxide (GO), alkaline solutions, and coarse and fine aggregates. The activators utilized were sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) and sodium hydroxide ( $\text{NaOH}$ ). The Islamabad chemical industries provided the alkaline sodium silicate chemical and sodium hydroxide in pellet shapes. The sodium silicate liquid comprises a  $\text{Na}_2\text{O}:\text{SiO}_2$  mass ratio of 1:2 ( $\text{Na}_2\text{O}$  13.9%,  $\text{SiO}_2$  27.8%). Sodium hydroxide liquid was prepared with 7 M by dispersing pellets of sodium hydroxide in water. The alkaline activator's solution was made one day before preparing the samples to guarantee the stabilization of the solutions. In the present research, riverbed sand from the Kabul river, Nowshera, was used as a fine aggregate, and crushed limestone was procured from the Hassan-Abdal stone quarry and used as a coarse aggregate. The physical properties of fine and coarse aggregates are provided in Table 1.

**Table 1.** Physical properties of fine and coarse aggregates.

Physical Property	Fine Aggregate	Coarse Aggregate
Maximum aggregate size (mm)	4.75	25.0
Fineness modulus	2.69	6.52
Specific gravity	2.65	2.78
Flakiness index (%)	-	11.0
Absorption (%)	1.23	1.06
Elongation index (%)	-	12.4
Impact value (%)	-	16.5

Fly ash (low calcium) was acquired from the local market in Islamabad, Pakistan, which follows ASTM C 618 [58], whereas GBFS was acquired from Pak Steel Re-Rolling Mills, Islamabad, Pakistan, following ASTM C 989 [59]. Figure 1 shows the X-ray fluorescent (XRF) spectra of fly ash and GBFS. XRF analysis depicts that a large quantity of silica ( $\text{SiO}_2$ ) and aluminum oxide ( $\text{Al}_2\text{O}_3$ ) is present in fly ash, while in GBFS, gypsum and silica were found in a large amount. The chemical compositions of GBFS and fly ash were obtained from the XRF analysis and are presented in Table 2. Graphene oxide powder at a 5 mg/mL concentration was acquired from the local commercial market, and extensive characterization is provided in the following section.

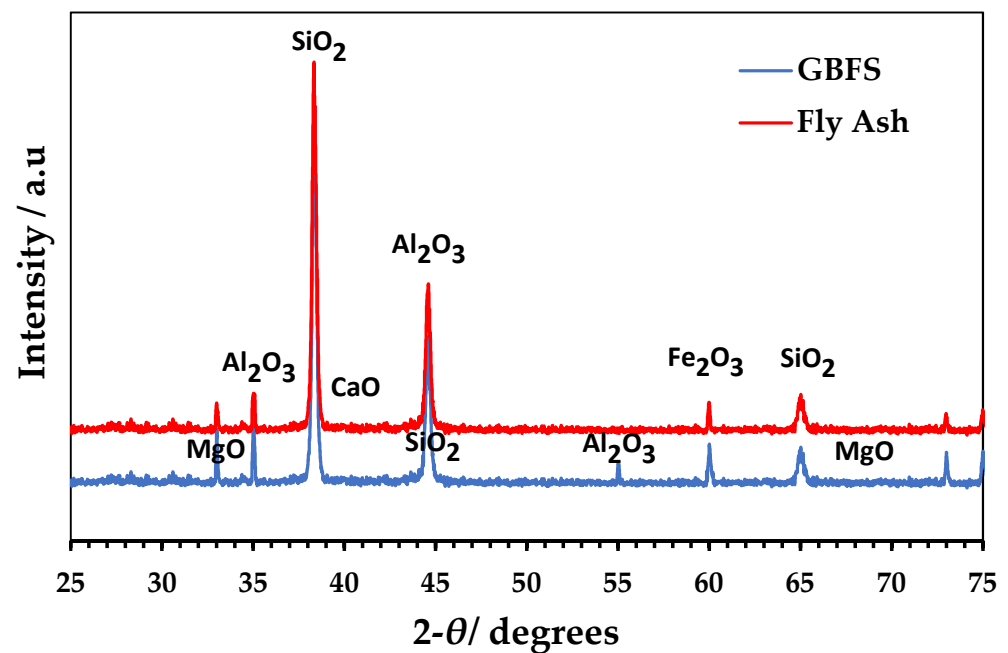


Figure 1. XRF spectra of fly ash and granulated blast furnace slag (GBFS).

Table 2. Chemical composition of GBFS and fly ash used as main raw material (% by mass).

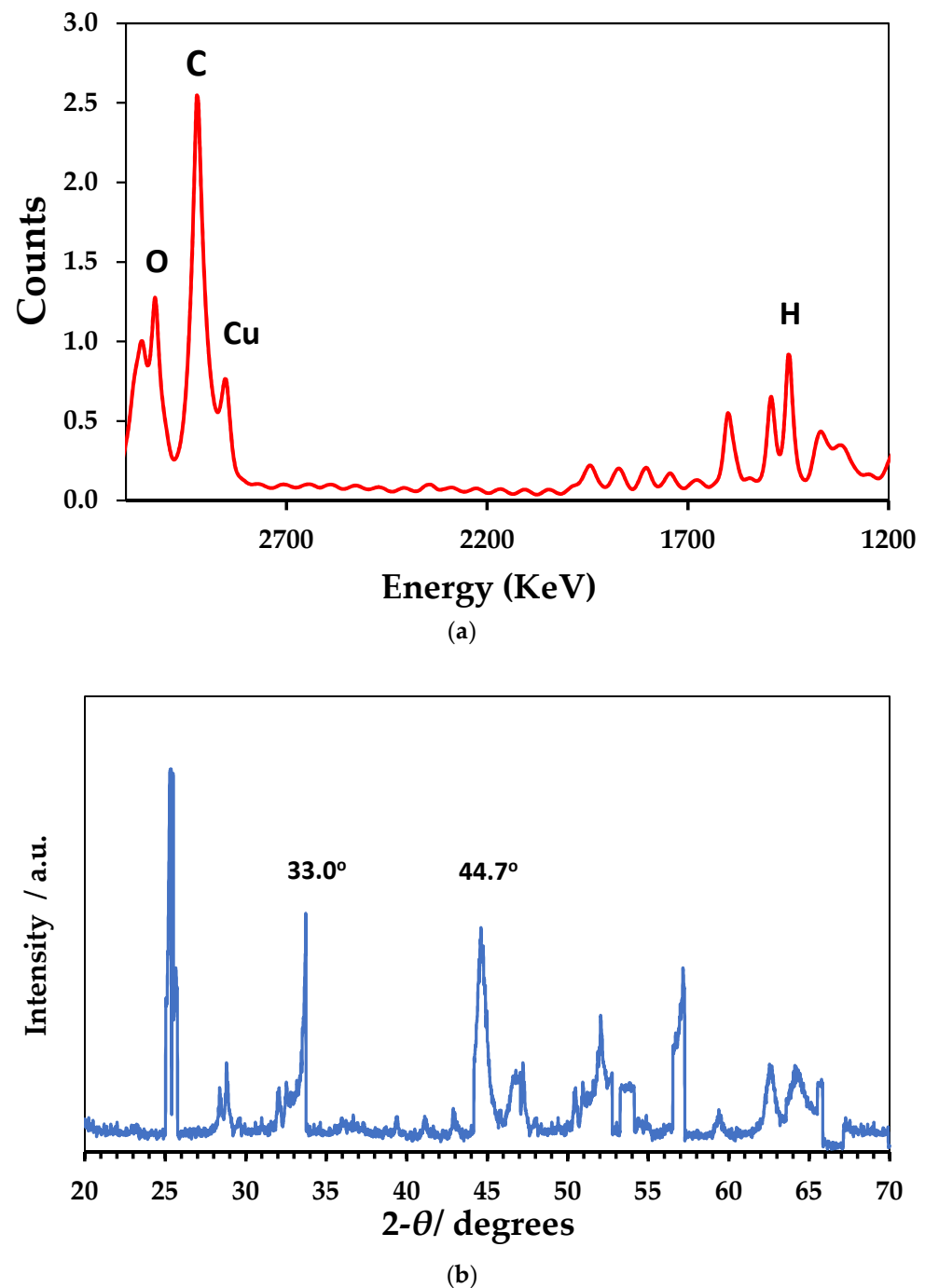
	LOI	SiO <sub>2</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	Na <sub>2</sub> O
GBFS	0.3	28.2	45.9	4.5	12.8	7.2	2.0	0.3
Fly ash	-	53.4	2.6	4.2	27.6	3.4	0.7	0.3

## 2.2. Characterization of Graphene Oxide (GO)

Complete Energy-dispersive X-ray (EDX) and X-ray diffraction (XRD) analyses were performed on graphene oxide. The EDX of graphene oxide is presented in Figure 2a, and the ratios of elemental atoms such as oxygen (O) and carbon (C) were 24.3% and 75.7%, respectively. It should be noted that the graphene oxide sample was placed on a sheet of copper during the testing process. For this reason, copper (Cu) signals might be noticed in the EDX results. The X-ray diffraction (XRD) spectra of graphene oxide are displayed in Figure 2b. The presence of diffraction peaks at  $2\theta = 33.7^\circ$  and  $2\theta = 44.7^\circ$  demonstrates an interlayer spacing of 0.783 nm, which is allocated to the (001) diffraction peak of graphene oxide. Similar results have been reported by past studies [60,61].

## 2.3. Mix Proportioning

Table 3 provides the complete mix proportioning of all samples defined based on previous investigations [62–65]. This study comprises three primary mixtures, with a different proportion of graphene oxide in each blend. In mix I.D., the terms “FA” and “G” stand for fly ash and GBFS, respectively, and denote the percentage of fly ash of GBFS in each mix. Similarly, “GO” stands for graphene oxide, and the number after indicates the amount of graphene oxide added to each blend.



**Figure 2.** (a) EDX and (b) XRD spectra of graphene oxide.

#### 2.4. Sample Preparation and Casting

Coarse and fine aggregates, GBFS, and fly ash were blended in a mechanical mixer for three minutes. Before mixing graphene oxide with the geopolymer material, sonication was permitted with an alkaline solution for sixty minutes. Afterward, the mix of graphene oxide and the alkaline solution was discharged into the mix of dry material and mixed in a mechanical mixer for 5 min. The fresh concrete was then poured into the molds (add dimension of the molds here). After twenty-four h of curing, the samples were demolded and water-cured at room temperature for 7, 28, 56, and 90 days. For every test of a specific mix, three samples were tested, and their average was taken as the final value to bring uniformity to the final results.

**Table 3.** Mixture proportion of specimens (kg/m<sup>3</sup>).

Mix ID	Description	Binder		Aggregates		G.O. (Grams)	Solution		H <sub>2</sub> O
		Fly Ash	GBFS	Coarse	Fine		NaOH	Na <sub>2</sub> SiO <sub>3</sub>	
M1 (FA85-G15)	M1-GO-0					0.00			
	M1-GO-0.05					20.87			
	M1-GO-0.15	354.83	62.61	1221	609	62.61	47.10	117.15	215
	M1-GO-0.25					104.36			
	M1-GO-0.35					146.10			
M2 (FA75-G25)	M2-GO-0					0.00			
	M2-GO-0.05					20.87			
	M2-GO-0.15	313.08	104.36	1221	609	62.61	47.10	117.15	215
	M2-GO-0.25					104.36			
	M2-GO-0.35					146.10			
M3 (FA65-G35)	M3-GO-0					0.00			
	M3-GO-0.05					20.87			
	M3-GO-0.15	271.34	146.10	1221	609	62.61	47.10	117.15	215
	M3-GO-0.25					104.36			
	M3-GO-0.35					146.10			

### 2.5. Testing Procedures

Concrete cylinders were prepared to perform compressive strength tests as per ASTM C39 [66] and the modulus of elasticity as per ASTM C 469 [67]. The resistance of GPC against the permeability of chloride ions was investigated by resorting to an NRA-1190 (RCPT) rapid chloride ions test apparatus using 220–240 V and a frequency of 50 kHz (Figure 3a). The test was performed by placing a concrete sample of 100 mm × 50 mm into the sample cell surrounded with 4% sodium chloride (NaCl) and 0.4 N normality of sodium hydroxide (NaOH) solution as per ASTM C1202 [68].

The thermal conductivity test was performed after 90 days of curing, following BS EN 12664 [20]. Thermal conductivity specimens were oven-dry for 24 h at the temperature of 103 ± 3 °C to eliminate any existing moisture. Figure 3b presents the schematic illustration of the thermal conductivity test equipment. The specimens were positioned amid cold and hot plates with temperatures of 35 °C and 20 °C, correspondingly, to stimulate thermal transfers. The temperature data on the cold and hot plates were recorded at 15 min intervals for 24 h. The average value of temperature was utilized to evaluate thermal conductivity. The concrete's sample thermal conductivity was assessed using Fourier's law as provided below in Equation (1):

$$k = \frac{(\Phi \times t)}{(A \times \Delta T)} \quad (1)$$

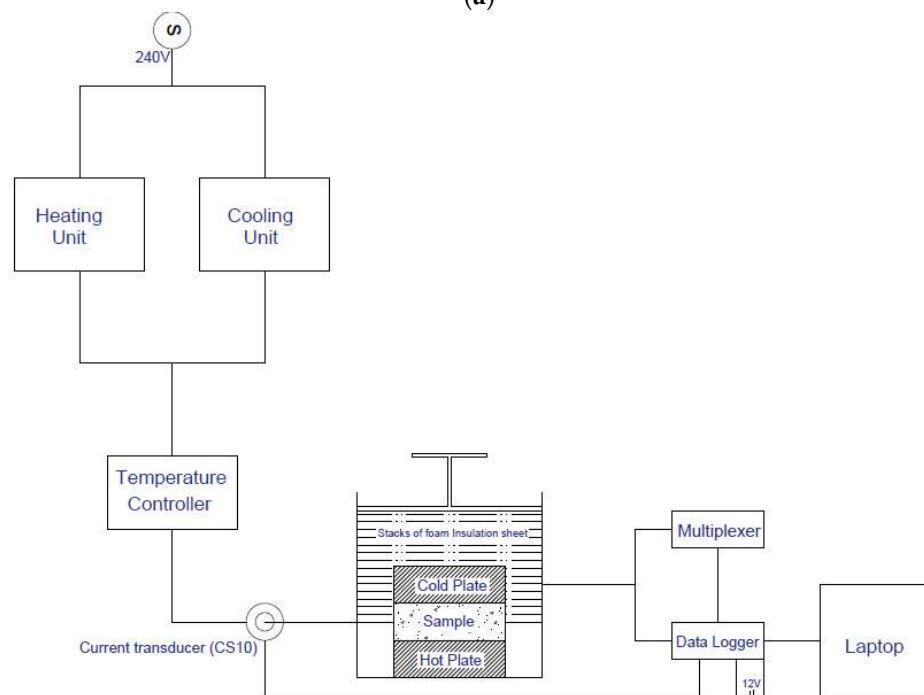
here

k = thermal conductivity (Watt per meter by Kelvin), t = sample thickness (m),  $\Phi$  = heat flow (Joule/sec),  $\Delta T$  = difference in temperature amid cold and hot plates (°C), and A = sample's area (m<sup>2</sup>).





(a)



(b)

**Figure 3.** (a) Test setup for RCPT, and (b) schematic illustration for a thermal conductivity.

### 3. Results and Discussion

#### 3.1. Compressive Strength

Figure 4 displays the compressive strength of GBFS-fly ash mixed GPC with 0.05 wt.%, 0.15 wt.%, 0.25 wt.%, and 0.35 wt.% inclusions of graphene oxide at different curing days (7, 28, 56, and 90 days). The geopolymer concrete strength is enhanced at yearly and later ages with graphene oxide addition. The compressive strength of graphene oxide- GPC specimens mostly relies on the chemical and physical interaction between the geopolymer matrixes and GO. A mechanical interlacement between the geopolymer binder and the wrinkled surface structure of the nanosheets of GO can possibly explain the enhancement in the strength characteristics obtained. The graphene oxide can possibly also behave like

a filler material in GPC and developing a dense structure, which paves the way to the improvement of compressive strength in the initial days [47]. The inclusion of 35 wt.% GBFS into specimens of GPC displayed improved strength characteristics with graphene oxide. The compressive strength of the 15 wt.% inclusion of GBFS into the reference mix (zero percent of graphene oxide) reached 40.12 and 42.31 MPa for ambient curing for 56 and 90 days, as presented in Figure 4. Geopolymer concrete with 0.5 wt. % graphene oxide obtained 51.04 and 52.43 MPa for ambient curing of 56 and 90 days.

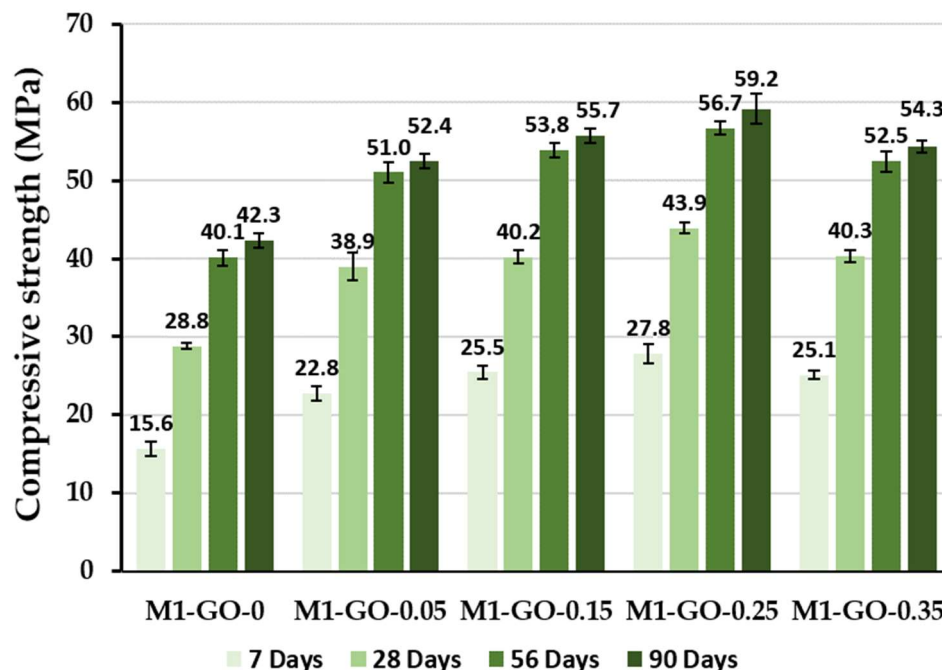


Figure 4. Compressive strength of M1 mix (FA85-G15).

Figure 5 presents the variance in the compressive strength of 25 wt.% GBFS in the GPC specimens. The results were evident when a low amount of graphene oxide was added to the GC, and the compressive strength was significantly enhanced at all curing ages. However, a 0.25 wt.% inclusion of graphene oxide seems to be an inflection point as displayed improved performance compared to other levels. The increase strength was obtained because of the wrinkled morphology and increased surface area of graphene oxide nanosheets. Because of the surface structure, the interconnected mechanism inside the mixtures of geopolymers was enhanced. The maximum strength was obtained at the inclusion of 0.25 wt.% graphene oxide by the binder weight utilized in the GPC. The compressive strength values are 55.74 MPa and 59.15 MPa at 56 and 90 days.

Moreover, at a 0.35 wt.% addition of graphene oxide, it was observed a reduction in compressive strength compared to the 0.25 wt.% graphene oxide-based GPC samples. The decrease in sample compressive strength can be related to the agglomeration of graphene oxide nanosheets in the geopolymer concrete because of the hydrophilic nature and high surface area. However, the strength in the early age of graphene oxide-modified GPC (M3-GO-0.25) was 35.58 MPa at 7 days and 51.39 MPa at 28 days, which is 70 and 91% higher than that of the reference sample (M3-GO-0). GPC mix proportion discussed here mainly stands on fly ash, which typically shows lower compressive strength when cured at room temperature [69]. From the laboratory results, graphene oxide was recognized to have a vital role in enhancing strength of FA-dominated GPC because of the dense matrix generated and high specific area of graphene oxide nanosheets [46].



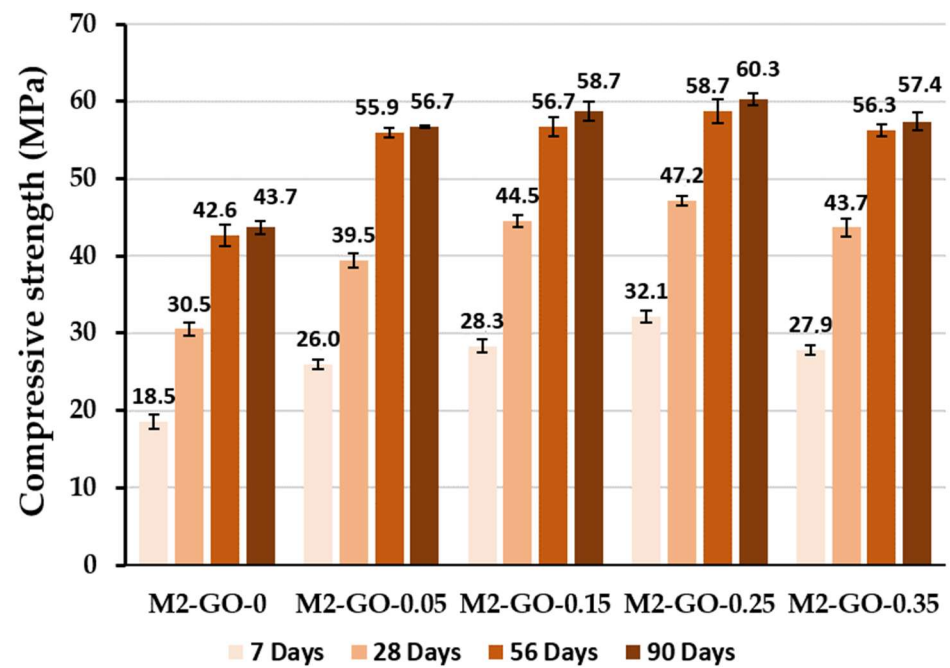


Figure 5. Compressive strengths of M2 mix (FA75-G25).

Figure 6 shows that the compressive strength of the control samples after 90 days was 48.62 MPa, which is improved by 26%, 30%, 34%, and 28% by the inclusion of 0.05 wt.%, 0.15 wt.%, 0.25 wt.%, and 0.35 wt.% graphene oxide, respectively. At 56 days of curing, the control sample compressive strength was 46.53 MPa, which is improved by 25%, 30%, 34%, and 30% by the inclusion of graphene oxide at 0.05 wt.%, 0.15 wt.%, 0.25 wt.%, and 0.35 wt.%, respectively. The significant improvement in strength can be established by adding graphene oxide connected to the extra development of calcium aluminosilicate (C-A-S-H) gel [70], as will be further discussed in Section 3.2.

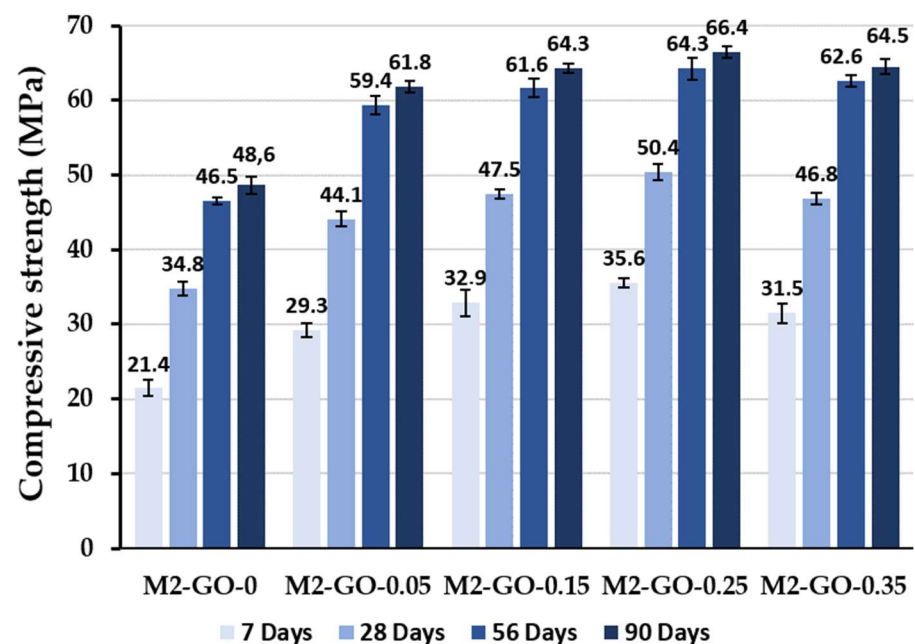


Figure 6. Compressive strengths of M3 mix (FA65-G35).

### 3.2. X-ray Diffraction (XRD) Analysis

X-ray diffraction analysis was performed on representative samples of M1 mix, M2 mix, and M3 mix with 0.25% GO at 90 days (Figure 7). Calcium silicate hydrate gel growth was noticed because of the nucleation of (C-S-H) by GO flakes [19]. The hydration process was accelerated when GO reacted with calcium hydroxide, developing calcium silicate hydrate gel; the developed C-S-H was noticed to be amorphous. Graphene oxide enhanced the mechanical strength, demonstrating a dense microstructure of the sample with low crystals of  $\text{Ca}(\text{OH})_2$  [49]. Figure 7 showed that the M3 mix has more intense silica, calcium silicate hydrate peaks, and calcium hydrate than other mixes. GO is a suitable strengthening material for the sample. The high content of quartz ( $\text{SiO}_2$ ) of fly ash and the dense structure of the sample is the significant reason behind the improved performance of geopolymer GO concrete.

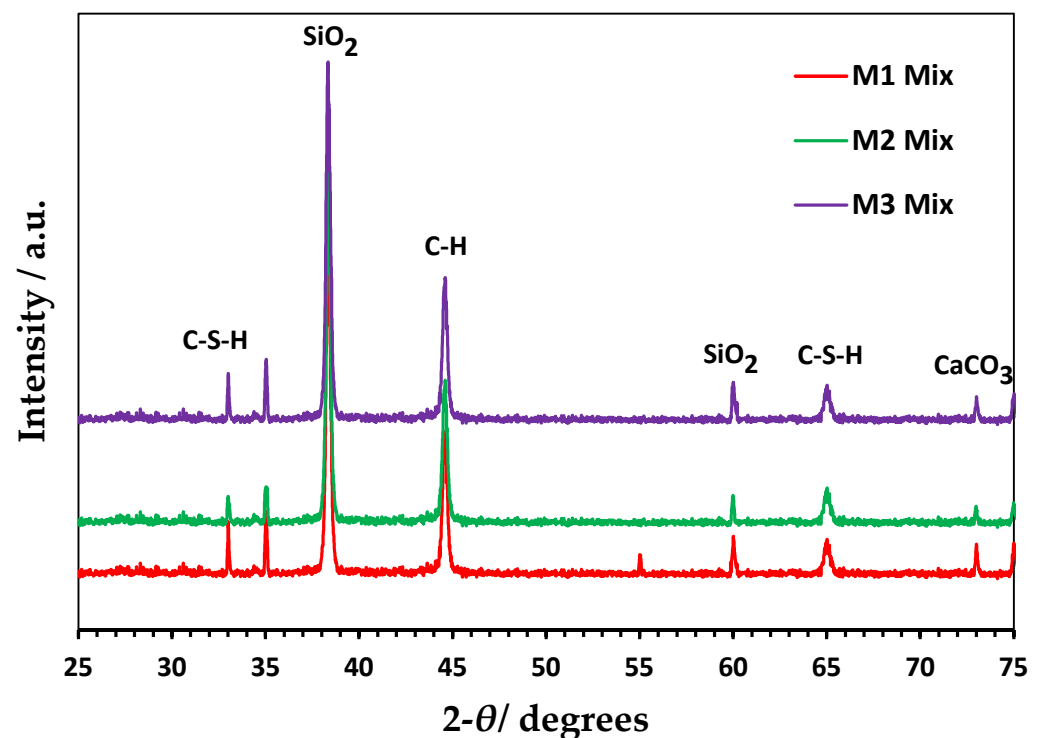


Figure 7. Comparative XRD analysis for all mixes of geopolymer G.O. concrete.

The presence of high content silicon, calcium, and oxygen in the M3 mix confirms the presence of GO sheets with the hydration products. Additionally, the improved hydration in the M3 mix and use of fly ash was the reason behind the higher silica content in the M3 mix. A rise in the proportion of  $\text{SiO}_2$  was also due to the formation of C-S-H gel produced due to hydration. Hence, the performance of GBFS-fly ash-based geopolymer concrete and GO is validated through the past studies [18,71,72].

### 3.3. Modulus of Elasticity (M.O.E.)

In Table 4, all the outcomes of the modulus of elasticity are presented. Compared to the compressive strength data, the GO-based geopolymer concrete modulus of elasticity was generally increased with GO inclusion. The moduli of elasticity for the M1-GO-0.05, M1-GO-0.15, M1-GO-0.25, and M1-GO-0.35 samples after ambient curing for 56 days were 29.85 GPa, 30.39 GPa, 33.34 GPa, and 31.69 GPa, and for the reference mix, the elastic modulus was 27.81 GPa.

Likewise, the moduli of elasticity for M2-GO-0.05, M2-GO-0.15, M2-GO-0.25, and M2-GO-0.35 samples after ambient curing for 56 days were 31.91 GPa, 32.67 GPa, 33.56 GPa, and 32.67 GPa, and for the reference mix, the elastic modulus was 28.72 GPa. The modulus

of elasticity values for the M3-GO-0.05, M3-GO-0.15, M3-GO-0.25, and M3-GO-0.35 samples after ambient curing for 56 days were 33.63 GPa, 34.16 GPa, and 36.12 GPa, and 35.34 GPa, and for the reference mix, the elastic modulus was 29.13 GPa. However, the inclusion of a lower amount of graphene oxide had a more significant effect on the modulus of elasticity of GBFS-fly ash-based geopolymer concrete [73]. An optimal outcome seems to be attained at 0.25 wt.% graphene oxide. The 35 wt.% inclusion of GBFS in fly ash-modified GPC with graphene oxide displayed better outcomes than the 15 wt.% and 25 wt.% GBFS counterparts, however.

**Table 4.** Values of projected M.O.E. from past studies, codes, and current research.

Mix ID	Description	Comp. Strength (MPa)	GPC Density (kg/m <sup>3</sup> )	Modulus of Elasticity (GPa)					Current Research
				Exp. 56 Days	[40]	[74]	[75]	[76]	
M1 (FA85-G15)	M1-GO-0	40.12	2329	27.81	30.38	30.64	28.54	26.17	26.78
	M1-GO-0.05	51.04	2347	29.85	34.92	33.37	31.65	30.06	30.98
	M1-GO-0.15	53.84	2361	30.39	36.19	34.22	32.45	31.14	32.04
	M1-GO-0.25	56.74	2373	33.34	37.29	34.97	33.25	32.15	32.99
	M1-GO-0.35	52.46	2376	31.69	35.94	34.22	32.58	30.98	31.82
M2 (FA75-G25)	M2-GO-0	42.63	2341	28.72	34.3	32.25	31.47	31.00	32.00
	M2-GO-0.05	54.92	2352	31.91	36.38	34.26	32.74	31.30	32.51
	M2-GO-0.15	56.74	2360	32.67	37.12	34.71	33.41	31.89	32.88
	M2-GO-0.25	58.74	2367	33.56	37.93	35.26	34.21	32.76	33.65
	M2-GO-0.35	56.31	2373	32.59	37.24	34.92	33.32	32.07	32.94
M3 (FA65-G35)	M3-GO-0	46.53	2352	29.13	34.3	33.85	32.45	31.00	32.00
	M3-GO-0.5	59.37	2368	33.63	38.18	35.42	33.84	32.85	33.74
	M3-GO-1.5	61.62	2386	34.16	39.22	36.15	35.1	33.75	34.86
	M3-GO-2.5	64.27	2385	36.12	40.21	36.7	35.6	34.36	35.75
	M3-GO-3.5	62.61	2396	35.34	39.78	36.56	35.45	33.21	35.26

Below are the equations described by previous studies and codes that have been used to predict the concrete modulus of elasticity.

(1) According to AS 3600 [74], the modulus of elasticity for Portland cement concrete ( $39 \text{ MPa} > f_c$ ) will be predictable utilizing Equation (2).

$$E_c = p^{1.5} (0.0243\sqrt{f'_c} + 0.11) \quad (2)$$

(2) According to ACI 318 [40], the modulus of elasticity for Portland cement concrete (density =  $1439\text{--}2478 \text{ kg/m}^3$ ) will be calculated by using Equation (3).

$$E_c = p^{1.5} (0.043\sqrt{f'_c}) \quad (3)$$

here,

$f_c$  = Average compressive strength of concrete (MPa) after 28 days

$p$  = Concrete density ( $\text{kg/m}^3$ )

$E_c$  = Modulus of elasticity (MPa)

$f'_c$  = Characteristics compressive strength (MPa) of concrete

(3) Mitra A et al., 2018 [75] proposed Equation (4) to evaluate the modulus of elasticity of graphene oxide-modified geopolymer concrete.

$$E_c = 0.035 \times p^{1.5} \times \sqrt{f'_c} \quad (4)$$

(4) Allouche E et al., 2011 [76] proposed Equation (5) to calculate the modulus of elasticity of geopolymer concrete.

$$E_c = 0.0385 \times p^{1.5} \times \sqrt{f'_c} \quad (5)$$

The lab result shows that the projected Equation (6) could be adopted to evaluate the M.O.E. of GBFS-fly ash-modified geopolymer concrete (MPa) from compressive strength with a reasonable degree of confidence. Figure 8 shows the suggested relationship to estimate the modulus of elasticity of graphene oxide-added G.P.C. after curing for 56 days.

$$E_c = 0.037 \times p^{1.5} \times \sqrt{f'_c} \quad (6)$$

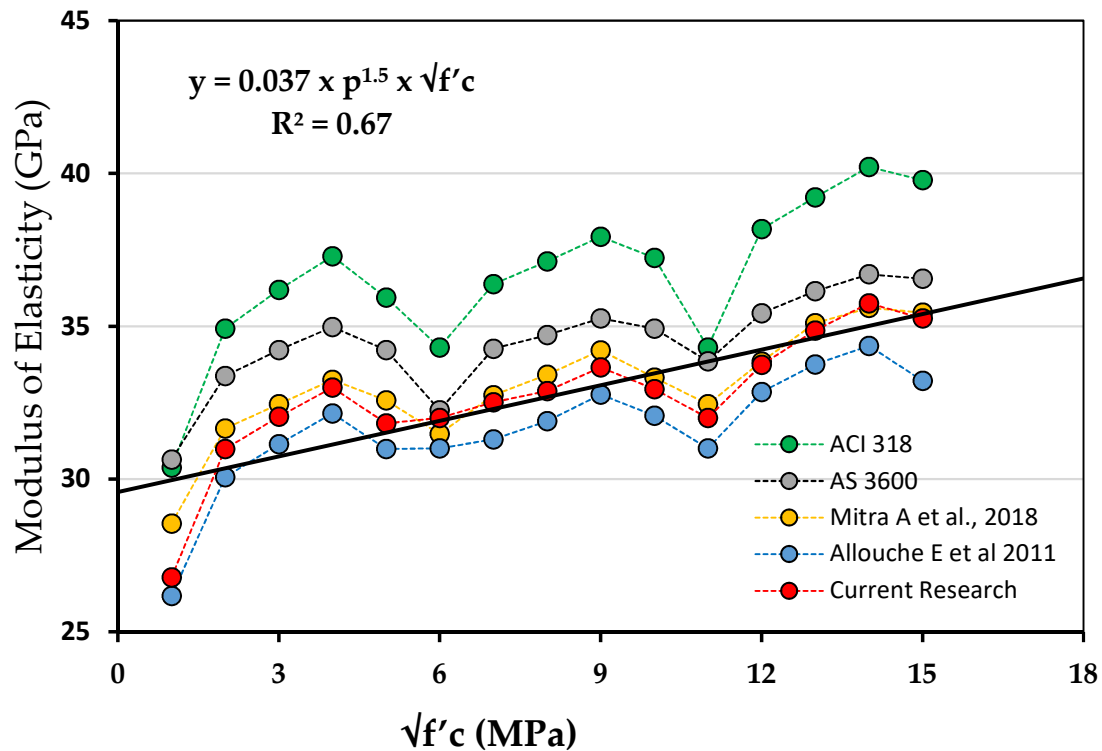


Figure 8. Projected relationship for the M.O.E. of graphene oxide G.P.C.

The attained outcomes on the geopolymer concrete modulus of elasticity from past studies, standard codes, and current research are provided in Table 4. A comparative analysis was performed to verify and validate our research with ACI 318, AS 3600 Code, and the present literature. From Figure 8, it can be noted that our testing values for M.O.E. lie well within the range of standard codes and past studies. GBFS-fly ash [77] with graphene oxide mixed GPC specimens [78] displayed higher values of modulus of elasticity than its GO-free counterparts.

### 3.4. Thermal Conductivity

The thermal conductivity test assesses the amount of heat conducted over a unit thickness perpendicularly to a unit of surface area under particular circumstances [79]. The thermal conductivity of graphene oxide alkali-activated concrete sample was contrasted with a sample with no graphene oxide (reference sample). As observed in Figure 9, the M3 samples (FA65-G35) showed the lowest thermal conductivity compared with the other mixes and reference samples; this test outcome is in line with other research works [4,42,43]. The test outcomes showed that the GO added samples display lower thermal conductivity than the reference sample [80]. The decreases in thermal conductivity were nearly 33%, 28%, and 21% for the M3 mix, M2 mix, and M1 mix, correspondingly, in comparison with the reference sample. As air has low thermal transmittance in comparison with liquid and solid state matter because of its atomic configuration [81], this assists by lowering the sample's thermal conductivity since more air is present in GO-containing concrete. Nambiar et al. [82] revealed that porous concrete has superior insulation characteristics

because of its cellular matrix, which can be analogous to the effect induced by honeycomb structure of GO.

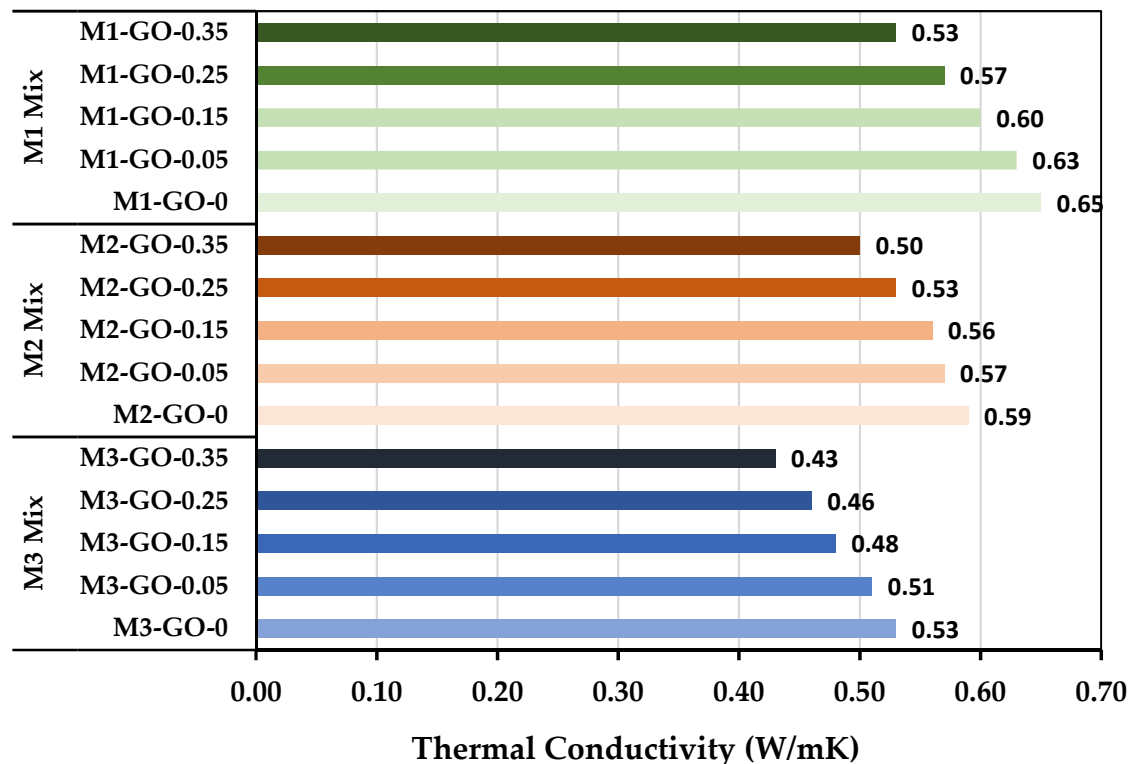


Figure 9. Thermal conductivity of samples.

### 3.5. Rapid Chloride Penetration Test (RCPT)

The electrical conductance over charge of the geopolymer concrete passed nearly 6 h after experimentation was recorded. The numbers were recorded every 60 min, and the trapezoidal law was followed. Equation (7) was utilized to evaluate the total charge passing the test specimen.

$$Q = 900(I_0 + 2I_{60} + 2I_{120} + \dots + 2I_{360}) \quad (7)$$

here,  $Q$  = Charge passed (in Coulombs);  $I_0, I_{60}, I_{120}, \dots, I_{360}$  is the current at 0, 60, 120, and 360 min.

ASTM C 1202 [68] was followed for this test. The outcome of penetration of chloride ions relies on the charge traveled. Table 5 shows the permeability of chloride ions for the graphene oxide-modified GBFS-fly ash mixed GPC samples. The RCPT test revealed that with increasing amounts of graphene oxide, the GBFS fly ash-modified GPC had an enhanced resistance against the permeability of chloride ions. However, there is a decrease in the traveled charge over M1-GO-0.25 samples compared to M1-GO-0, M1-GO-0.05, M1-GO-0.15, and M1-GO-0.35 specimens. For the M1-GO-0.25 specimens, the permeability was minimal, which could be ascribed to the increased addition of graphene oxide. The reference sample (M1-GO-0) had the maximum permeability of chloride ions. The samples with graphene oxide up to 0.25 qt. % exhibited improved resistance against the permeability of chloride ions. However, sample M3-GO-0.25 comprises 75 wt.% fly ash and 35 wt.% GBFS, and 0.25 wt.% graphene oxide displays the minimum permeability of chloride ions compared to the other samples. The same sample also showed improved compressive strength, suggesting that a 0.25 wt.% is most likely the optimum dosage for graphene oxide inclusion.

**Table 5.** Lab outcomes of a rapid chloride penetration test.

Mix ID	Description	Charge Traveled (Coulombs)	Penetration (ASTM C 1202) [68]	
M1 (FA85-G15)	M1-GO-0	4147	<4000	High
	M1-GO-0.05	3164	2000–4000	Moderate
	M1-GO-0.15	2565		
	M1-GO-0.25	1721	1000–2000	Low
	M1-GO-0.35	2076	2000–4000	Moderate
M2 (FA75-G25)	M2-GO-0	3869	2000–4000	Moderate
	M2-GO-0.05	2563		
	M2-GO-0.15	1879	1000–2000	Low
	M2-GO-0.25	1568		
	M2-GO-0.35	1704		
M3 (FA65-G35)	M3-GO-0	3395	2000–4000	Moderate
	M3-GO-0.5	2241		
	M3-GO-1.5	1594	1000–2000	Low
	M3-GO-2.5	1169		
	M3-GO-3.5	1427		

#### 4. Conclusions

The present research focuses on the influence of adding graphene oxide to GBFS-fly ash-based geopolymer concrete. Different characterization tests were performed including mineralogical analysis, compressive strength, modulus of elasticity, and rapid chloride penetration. The results were compared with previous data from extant codes and available literature. Based on the present research, the following conclusions can be drawn:

- Adding GO to GBFS-fly ash-based GPC improved compressive strength values compared to the control specimen. Among various doses of graphene oxide (0.05 wt.%, 0.15 wt.%, 0.25 wt.%, and 0.35 wt.%), the utmost improved compressive strength was obtained in the geopolymer concrete specimen with 0.25 wt.% graphene oxide.
- The high surface area of graphene oxide behaved as a filler that filled the gaps and improved the compressive strength characteristics of GPC.
- The proposed relationship (Equation (6)) lies well within the range of existing codes and past studies, meaning that the proposed equation in present research  $E_c = 0.037 \times p^{1.5} \times \sqrt{f'_c}$  ("F") can be adopted to accurately estimate the M.O.E. of graphene oxide-added GBFS fly ash-based GPC cured in water at room temperature.
- When G.O. was added by more than 0.25 wt.%, the strength began to decrease.
- The M.O.E. of graphene oxide-added GBFS fly ash-based G.P.C. was improved by 21–27% compared to the reference GP. samples after curing for 56 days.
- The XRD test showed a mineralogy of different from which the suitability of graphene oxide in geopolymer concrete was confirmed.
- The thermal conductivity of GPC GO modified samples depicted that the M3 mix had the lowest thermal conductivity (about 33%) lower than other mixes.
- The RCPT test recognized the unprecedented resistance capacity of graphene oxide GPC samples against the permeability of chloride ions. At an optimal dose of graphene oxide (0.25 wt.%), the permeability of chloride ions was the lowest recorded (add value here).

#### 5. Future Recommendations

The present study recognizes various parameters that affect the characteristics of graphene oxide-added GBFS-fly ash-based geopolymer concrete. The GBFS-fly ash-based geopolymer samples with graphene oxide displayed excellent performance in all the tests. More studies must be undertaken to explore the possible applications of geopolymer material utilizing graphene oxide. This will pave the way to explore fields that focus on



using green or waste materials [83] in real-world applications to bring sustainability to their respective industries. The technology of geopolymers is imminent to go beyond the concrete industry, and there is also a likelihood that geopolymer, an environmentally friendly and sustainable binder, can be adopted in other industrial sectors [53].

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## Abbreviations

Modulus of elasticity (M.O.E.), Fly ash (F.A.), Geopolymer concrete (G.P.C.), Graphene oxide (G.O.), Rapid chloride penetration test (RCPT), Granulated blast furnace slag (GBFS), Alkali activated-materials (A.A.M.).

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